GALLIUM

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Gallium metal and gallium arsenide (GaAs) wafer imports continued to supply most of the U.S. gallium demand. Metal imports were 36% higher than those in 2003, with China, Japan, and Ukraine as the principal import sources. Undoped GaAs wafer imports were 75% less than those in 2003; Canada was the principal source. Almost all of the gallium consumed in the United States was in the form of GaAs, which was used in integrated circuits (ICs) and optoelectronic devices [laser diodes, light-emitting diodes (LEDs), photodetectors, and solar cells]. An upturn in the wireless communications market resulted in a 7% increase in gallium consumption. New devices with gallium nitride (GaN) components, such as DVD players with GaN laser diodes, were introduced in 2004, and additional products incorporating GaN devices were planned.

In 2004, estimated world crude gallium production was 70 metric tons (t), about the same as that in 2003. Principal producers were China, Germany, Japan, and Ukraine; gallium also was recovered in Hungary, Kazakhstan, Russia, and Slovakia. Refined gallium production was estimated to be about 87 t, which included some new scrap refining. A gallium recovery plant in China reopened in 2004, while the gallium recovery plant in Germany reduced its operating rate, and the gallium recovery plant in Kazakhstan closed.

Legislation and Government Programs

The U.S. Department of Energy selected 11 research projects to fund for fiscal year 2005 under its solid-state lighting initiative. Slightly less than one-half of the overall figure of $20 million is earmarked for work directly relating to compound semiconductor materials, and the remainder will be spent on organic alternatives. Of the six compound semiconductor projects, the one to receive the most funding ($4.2 million) was a 3-year project that will focus on the development of advanced phosphors used to convert blue LED emission into white light (U.S. Department of Energy, 2005§[1]).

The U.S. Department of Commerce's Advanced Technology Program (ATP), which is managed by the National Institute of Standards and Technology, funded 32 new projects in its September 2004 round of awards. Three of the projects involve compound semiconductor technologies. The biggest of these projects is focused on white LED lamps for solid-state lighting, which was awarded to the team of Cree Inc. and Nanocrystal Lighting Corp. Total funding for the 3-year project was about $7 million, with $3.4 million supplied by ATP. The project goal is to demonstrate an LED-based lamp with an integrated chip approach that would more than quadruple the brightness and double the efficiency of existing LED systems. If successful, such a development could reduce the cost per lumen of LED lamps to a point where their introduction for general solid-state lighting could be accelerated by 3 years (U.S. Department of Commerce, 2004§).

Production

No domestic production of primary gallium was reported in 2004 (table 1). Recapture Metals Inc. in Blanding, UT, recovered gallium from scrap materials, predominantly those generated during the production of GaAs. Recapture Metals' facilities have the capability to produce about 40 metric tons per year (t/yr) of high-purity gallium. The company recovered gallium from its customers' scrap on a fee basis and purchased scrap and low-purity gallium for processing into high-purity material.

On March 18, GEO Specialty Chemicals Inc. filed for Chapter 11 protection in the U.S. Bankruptcy Court for the District of New Jersey. GEO Gallium (a subsidiary of GEO Specialty Chemicals) produced gallium from a plant in Germany and refined gallium at a plant in France. The privately held company emerged from bankruptcy on December 31 after its reorganization plan was approved by the court. Through its reorganization, GEO has discharged more than $135 million of unsecured obligations and canceled its prepetition common shares and warrants (Geo Specialty Chemicals Inc., 2005§).

Gold Canyon Resources Inc. hired the firms of Kappes, Cassidy & Associates and ChelaTech Corp. To conduct simultaneous metallurgical studies on mineralization from its Cordero gallium project in Humboldt County, NV. Both programs were underway, and these metallurgical programs were intended to improve extraction of gallium at Cordero (Gold Canyon Resources Inc., 2004§). Win-Eldrich Mines Ltd. did not report any progress on its Painted Hills gallium deposit in Humboldt County.

Consumption

More than 95% of the gallium consumed in the United States was in the form of GaAs. GaAs was manufactured into optoelectronic devices (LEDs, laser diodes, photodetectors, and solar cells) and ICs. ICs accounted for 46% of domestic consumption, optoelectronic devices accounted for 36%, 17% was used in research and development, and about 1% was used in other applications (tables 2, 3).

Gallium consumption data were collected by the U.S. Geological Survey from a voluntary survey of U.S. operations. In 2004, there were nine responses to the consumption of gallium survey, representing 39% of the total canvassed. Data in tables 2 and 3 were

[1]References that include a section mark (§) are found in the Internet References Cited section.

adjusted by incorporating estimates to reflect full industry coverage. Many of these estimates were based on the companies' 2004 10-K reports submitted to the Securities and Exchange Commission.

Gallium Arsenide.—Teledyne Technologies Inc., through its subsidiary Teledyne Wireless, acquired Celeritek Inc.'s defense electronics business for $33 million. Celeritek's defense business was based in Santa Clara, CA, where it manufactured GaAs-base components and subassemblies for electronics warfare, radar, and other military applications. Teledyne planned to relocate this business to Mountain View, CA, where it already had a defense establishment. As part of the agreement, Celeritek will continue to supply GaAs semiconductor components to Teledyne for use in defense subsystems (Compound Semiconductor, 2004l).

RF Micro Devices Inc. (RFMD) planned to spend $75 million on an expansion of 6-inch-diameter wafer processing capacity at its GaAs fabrication facility in North Carolina. The company was expected to add 75 jobs as a result. The cellular telephone handset sector was the primary market for RFMD's products (Compound Semiconductor.net, 2004i§).

In the first half of 2004, RFMD began shipments of its quad-band power amplifier module to a major cellular telephone handset manufacturer. The quad-band module is based on GaAs heterojunction bipolar transistors (HBTs), and the company claimed that this was the smallest type of this module available. All four bands are integrated into a single GaAs HBT die in the module, which RFMD says is 75% smaller than its previous-generation component (Compound Semiconductor.net, 2004h§).

Sensors Unlimited Inc. introduced Visible-InGaAs, the world's smallest dual wavelength range camera that simultaneously images in the visible and shortwave infrared spectrum. Currently in use by the U.S. Department of Defense, the camera's use includes imaging of all military laser designators, even those invisible to the human eye. With the simultaneous dual wavelength capabilities, the company's new camera expands current night-vision technology and can perform many other jobs that formerly required two separate cameras (Sensors Unlimited Inc., 2004§).

Solar cells manufactured by Spectrolab Inc. (a subsidiary of Boeing Co.) provided power to Spirit and Opportunity, the National Aeronautics and Space Administration (NASA)-built Mars rovers that landed in January to explore the planet. The solar cells aboard "Spirit" and "Opportunity" are gallium indium phosphide (GaInP)/GaAs/germanium triple-junction cells and use the three-layered structure to capture and convert solar energy into electricity. Each of the junctions converts a different portion of the solar spectrum into electricity. The solar panels were folded to fit inside the rovers for the trip to Mars. Once on the Martian surface, the solar panels deployed to form a total area of 1.3 square meters. The solar cells power all the activities and instruments of the rovers (Spectrolab Inc., 2004§).

EMCORE Corp. was selected by Boeing to provide advanced triple-junction high-efficiency solar cells and panels for the latest model 702 satellite that Boeing is manufacturing. The contract includes an option for a follow-on satellite as well. The triple-junction cells feature an indium gallium phosphide (InGaP)/GaAs/germanium layer structure on top of a germanium substrate and are manufactured using metal-oxide chemical vapor deposition (MOCVD). These three junctions absorb sunlight over a wavelength range of 300 to 1,700 nanometers (nm). The satellite is able to generate 18 kilowatts (kW) of power at start of service and 15.5 kW at the end of its 15-year design life (Compound Semiconductor, 2004c).

Gallium Nitride.—Cree Inc. purchased ATMI Inc.'s GaN epitaxy and substrates businesses for $10.25 million in April. With the purchase, Cree acquired 17 U.S. patents and additional patent applications, which complement its existing intellectual property business and include a U.S. patent for white LEDs and related technology (Compound Semiconductor, 2004b). Cree also announced that it would invest $300 million during the next 5 years to increase manufacturing capacity and create more than 300 jobs. The company planned to transfer its LED growth process to 3-inch-diameter substrates, which would take about 1 year to complete and would result in double the number of production chips per wafer. Cree's other plans included increasing LED production capacity in fiscal 2005 by spending $100 million to $120 million on equipment (Hatcher, 2004a).

In January, Picogiga International (a division of Soitec Group) introduced a family of advanced aluminum gallium nitride (AlGaN)-GaN epitaxial layers on 2-, 3-, and 4-inch-diameter silicon substrates. These GaN-on-silicon epitaxial wafers were designed to be used as high-power high-electron mobility transistor (HEMT) structures in wireless infrastructure and other high-speed applications. Most AlGaN-GaN HEMTs are grown on sapphire or silicon carbide (SiC) substrates. Although silicon is desirable as a substrate material because of its lower cost, high quality, and availability, it has been shown to be the most difficult substrate on which to grow compound semiconductor layers, particularly GaN. Picogiga claimed that its molecular beam epitaxy (MBE) deposition process overcomes the challenge of growing GaN on silicon, allowing both the material properties of GaN and the advantages of silicon substrates to be combined (Compound Semiconductor, 2004g). Another company working on GaN-on-silicon technology, Nitronex Corp., began selling 100-millimeter-diameter GaN-on-silicon epitaxial wafers in July.

Technologies and Devices International Inc. (TDI) announced a technical breakthrough by fabricating the industry's first 6-inch-diameter GaN epitaxial wafers. The 6-inch-diameter GaN-on-sapphire epitaxial wafers were fabricated using TDI's patented hydride vapor-phase epitaxial (HVPE) process and equipment. Demonstration of 6-inch-diameter GaN epitaxy was a specific result of a Phase I Small Business Innovation Research (SBIR) Program contract awarded to TDI by the U.S. Missile Defense Agency (Compound Semiconductor, 2004k).

II-VI Inc., Saxonburg, PA, and Sensor Electronic Technology Inc. (SET), Columbia, SC, signed a joint marketing and sales agreement for III-nitride epitaxial wafers produced by SET on SiC substrates manufactured by II-VI. The two companies planned to market their products in Germany, Japan, and the United States. The initial product portfolio included quaternary aluminum indium gallium nitride (AlInGaN)-base 2- and 3-inch-diameter epitaxial wafers on SiC substrates and also 2-, 3-, and 4-inch-diameter epitaxial wafers on sapphire substrates. In addition, the companies were sampling 2- and 3-inch-diameter AlInGaN-GaN heterojunction field-effect transistors wafers for fabrication of ultrahigh power transistors, which are important building blocks for microwave power amplifiers (MPAs). MPAs amplify radio-frequency signals and are central pieces in transmit/receive modules of both military and commercial radars and communications systems, including networks of base stations for wireless communications (cellular telephones and the Internet). The development of this technology has been supported by the U.S. Government with funding through various programs (Compound Semiconductor.net, 2004a§).

Several companies planned to begin mass-producing blue GaN-base laser diodes in 2005, primarily for use in the DVD market. NEC Compound Semiconductor Devices Ltd. was expected to begin sample shipments in the first half of 2005. Toshiba Corp. was reported to be starting mass production of lasers in the first half of 2005, as well as releasing a DVD recorder. Matsushita Electrical Industrial Co. Ltd. recently released a DVD recorder featuring a blue laser made by Nichia Corp. and planned to introduce products featuring its own lasers next year. Other firms that were expected to release products were Sony Corp., Sharp Corp., and Sanyo Electric Co. Ltd. Nichia planned to invest $45 million to increase production capacity of GaN blue laser diodes to 250,000 units per month (Compound Semiconductor, 2004e).

Several blue laser diode users have chosen between the two competing formats—Blu-ray and high-definition DVD (HD-DVD)—for their products. Sony, which has invested in the development of Blu-ray technology, has chosen that format for the successor to its PlayStation games console. HD-DVD is promoted by Toshiba, NEC, and Sanyo, and backed by four major film studios—New Line Cinema (a subsidiary of Time Warner Corp.), Paramount Pictures Corp., Universal Studios Inc., and Warner Brothers Inc. Sony Pictures Entertainment and MGM Studios (subsidiaries of Sony) and The Walt Disney Co. (and its home video division, Buena Vista Home Entertainment) planned to support the Blu-ray format. 20th Century Fox (a subsidiary of Fox Entertainment Group Inc.) has not yet decided which format to support, but it is likely to be Blu-ray (LaborLawTalk.com, undated§). In addition, Sony and Matsushita Electric (manufacturer of products under the Panasonic brand name) plan to incorporate Blu-ray technology in new camcorders that the companies plan to release in 2005.

Light-Emitting Diodes.—Many LED manufacturers introduced new LEDs based on GaAs and GaN technology that offer improvements from currently produced LEDs. In many cases, the new LEDs are brighter, last longer, and/or can be used in new applications. These new products have applications that include automotive lighting, cellular telephones, entertainment and decorative lighting, and signage.

In August, Sony introduced what it believes is the world’s first LED-backlit liquid crystal display (LCD) television using Luxeon® LEDs manufactured by Lumileds Lighting U.S. LLC. Sony is reported to have launched two flat-screen televisions that feature the new technology—a 40-inch and a 46-inch version. Typically, red colors tend not to reproduce well with conventional backlights used in flat-screen televisions. With LED backlighting, the red colors are displayed much more strongly. Available in Japan initially, the models were expected to be released to overseas markets by the beginning of 2005. Earlier in the year, NEC Display Solutions of America Inc. (formerly NEC-Mitsubishi Electronics Display of America Inc.) introduced an LCD prototype 23-inch flat-panel monitor that uses Lumileds Luxeon® LEDs for backlighting. In September, Samsung Electronics Co. Ltd. introduced several LCD display monitors with LED backlighting, including 17-inch and 21-inch panels and a one-piece touch screen panel for small LCDs used in cellular telephones (Compound Semiconductor, 2004j).

The Fox Group, a startup LED manufacturer in Ripon, CA, developed a production method for manufacturing blue GaN-base LEDs by HVPE. The company opened a manufacturing facility in Montreal, Quebec, Canada, and by mid-May, had shipped its first order of 460-nm FoxBlue™ LEDs. Compared with MOCVD, which is used by all other manufacturers of blue GaN-base LEDs, HVPE is estimated to reduce the use of ammonia by at least an order of magnitude. Also, HVPE uses pure metals as starting materials rather than metalorganic precursors, which are about 10 times more expensive per gram of metal. The fast growth rate of HVPE and the simpler device structure also help to reduce the overall cost of the process. The HVPE technology used to grow LEDs was originally developed by TDI (Whitaker, 2004).

Lumileds opened a new plant in Malaysia to meet growing demand for its Luxeon® LEDs. The new plant will be in a 200,000-square-foot building that the company purchased near its current rented space in Penang and will replace the current factory. Manufacturing at the new plant began at the end of April, with simultaneous production at the old and new facilities to avoid disruption in supply while the new factory was brought online. The move was completed by the beginning of July (Compound Semiconductor, 2004f).

Toyoda Gosei Co. Ltd., a Japanese manufacturer of GaN-base LEDs, began construction of a facility in Takeo City, Saga Prefecture, which will serve as the company’s second production base. The company operated one facility in Heiwacho, Aichi Prefecture. Toyoda Gosei planned to invest ¥1.6 billion ($14 million) in the project in 2004, ¥7 billion ($63 million) in 2005, and an additional ¥7 billion in 2006. Construction on the new facility began in April 2004, and LED production was scheduled to begin in May 2005. Monthly production capacity at the new plant will increase from an initial level of 29 million chips to 130 million chips in 2005 and 200 million chips in 2006 (Compound Semiconductor, 2004m).

Showa Denko K.K. developed a 12-milliwatt blue LED and will start marketing the product in 2005 for applications such as mobile phones, outdoor displays, illumination and automotive devices. The company was constructing a plant in Chiba, Japan, to produce 30 million units per month of GaN-base blue LED chips. Sample shipment began in November, with commercial production commencing next year. Showa Denko planned to sell 30 million units per month by yearend 2005 (Compound Semiconductor, 2004i).

Prices

Since 2002, producer prices for gallium have not been quoted in trade journals. Data in table 4 represent the average customs value of gallium imported into the United States. Reports in Mining Journal indicated that gallium prices rose slightly during 2004. At the beginning of the year, low-grade gallium prices were reported to be about $250 to $300 per kilogram. By April, the price increased to slightly more than $300 per kilogram, where it remained until yearend.

From U.S. Census Bureau import data, the average value for low-grade gallium was estimated to be $192 per kilogram, about 15% lower than the average value in 2003. For high-grade gallium, the average estimated value rose to $494 per kilogram from $411 per kilogram. Import data, reported by the U.S. Census Bureau, does not specify purity, so the values shown in table 4 are estimated based on the average value of the material imported and the country of origin.

Foreign Trade

In 2004, U.S. gallium imports were 36% higher than those in 2003 (table 5). Japan (28%), China (24%), Ukraine (15%), and Hungary (12%) were the leading sources of imported gallium. U.S. consumption of gallium metal has diminished mainly because a significant portion of the GaAs manufacturing capacity has moved to other countries, such as China and Taiwan. Gallium metal imports, therefore, are not expected to be as large as they have been in the past several years.

In addition to gallium metal, GaAs wafers were imported into the United States (table 6). In 2004, 3,580 kilograms (kg) of undoped GaAs wafers and 226,000 kg of doped GaAs wafers were imported. Undoped GaAs wafer imports were 75% less than those in 2003, but imports of doped GaAs wafers were 78% higher than those in 2003. The data shown in table 6 may include some packaging material and, as a result, may be higher than the actual total weight of imported wafers.

World Review

Imports of gallium into Japan and the United States, the two leading consuming countries, have been used as the basis for estimating world gallium production. Estimated crude gallium production was 70 t in 2004. Principal world producers were China, Germany, Japan, and Ukraine. Gallium also was recovered in Hungary, Kazakhstan, Russia, and Slovakia. Refined gallium production was estimated to be about 87 t; this included some new scrap refining. France was the largest producer of refined gallium using gallium produced in Germany as feed material. Japan and the United States also refined gallium. Gallium was recycled from new scrap in Germany, Japan, the United Kingdom, and the United States.

The non-Japan Asian region of China, the Republic of Korea, and Taiwan produced the world's largest volume of high-brightness LEDs (HB-LEDs) in 2003, according to a report from Strategies Unlimited (a research unit of PennWell Corp.). According to the report, the region produced 13.4 billion indium gallium aluminum phosphide (InGaAlP)-base LED chips, a 25% increase from the 2002 figure that represented 80% of the world total. In addition, the region produced 40% of the world's GaN-base LED chips, amounting to 3.4 billion in 2003. Taiwan was the leading manufacturing center in non-Japan Asia, with 87% of InGaAlP epitaxial wafers fabricated in Taiwan. China accounted for 10%, and the Republic of Korea, 3%. The region's GaN wafer production in 2003 was more balanced, with 73% produced in Taiwan, 16% in the Republic of Korea, and 11% in China (Hatcher, 2004c).

China.—Shandong Aluminium Corp. restarted gallium production at its 20-t/yr extraction facility in April, but was only producing about 400 kilograms per month. The facility had been closed in mid-2003 because of low gallium prices (Metal-Pages, 2004c§). In addition, the Henan Branch of China Aluminum Co. Ltd. reportedly began commercial production of 99.99%-pure gallium at its plant in Zhengzhou City, Henan, in mid-2004. The company had the capacity to produce crude gallium, but improved the purity by improving its production technology (Metal-Pages, 2004a§).

One of China's arsenic producers, Hengyang Fenghuang, announced that it would recover gallium from GaAs scrap. The company planned to process 3 to 5 metric tons per month (t/mo) of GaAs scrap to produce 1 t/mo of gallium. The company claimed to be able to produce 99.9999%-pure gallium (Metal-Pages, 2004b§).

Germany.—GEO Gallium reduced production at its Stade gallium extraction facility to one-third of its 35-t/yr capacity in March because of low gallium prices and market oversupply. The company also announced that it had deferred investing in its 50-t/yr Pinjarra, Australia, extraction facility and had no plans to restart it (Compound Semiconductor.net, 2004e§).

Japan.—In 2004, Japan's virgin gallium production was estimated to be 9 t, gallium recovered from scrap was reported to be 83 t, and gallium imports were reported to be 48 t, for a total supply of 140 t. France, Kazakhstan, and the United States were estimated to be the principal sources of gallium imported into Japan.

Kazakhstan.—Kazakhstan Aluminium closed its 20-t/yr gallium extraction plant in the northern Pavlodar region in March citing unfavorable world market economics (Rusmet.net, 2004§).

Taiwan.—Procomp Informatics Ltd., a GaAs chip producer based in Taiwan, sought bankruptcy protection on June 16, the day before it had to make a corporate bond payment. Taiwanese authorities, however, began an investigation into the company's finances after it appeared that the company had enough money to make the scheduled bond payment. The bankruptcy filing and ensuing investigation also led to the collapse of one of Procomp's joint ventures, Suntek Compound Semiconductor Co., an HBT foundry, which claimed to be Taiwan's largest GaAs IC manufacturer (Hatcher, 2004d).

In October, WIN Semiconductors Corp. and Global Communication Technology Corp. (GCT) announced that they planned to merge the two companies, which would create Taiwan's largest GaAs foundry. WIN was scheduled to increase its monthly 6-inch-diameter wafer production from 1,100 to 1,600 wafers, and earlier in 2004, GCT had announced that it would increase its monthly 6-inch-diameter wafer production to 1,200. The combined capacity would make the merged firm larger than the one remaining Taiwanese GaAs foundry, Advanced Wireless Semiconductor Co. In 2003, GCT had announced a merger with U.S. firm Global Communication Semiconductors Inc., but this merger never took place (Stevenson, 2004c).

In July, Arima Optoelectronics Corp., a manufacturer of LEDs and laser diodes, merged with Kingmax Optoelectronics Inc., a manufacturer of epitaxial wafers. The merger was designed to increase Arima's capacity for aluminum gallium indium phosphide (AlGaInP) HB-LEDs by acquiring Kingmax's four MOCVD machines with an equivalent capacity of 250 million units per month; this would bring Arima's capacity to 450 million units per month (Compound Semiconductor, 2004a). In addition, Arima began shipping high-luminance blue LEDs in the third quarter. It also installed additional MOCVD capacity between August and October, which led to a monthly production of 100 million units by yearend. AlGaInP LED maker Tyntek Corp. also planned to double production to between 80 million and 100 million units per month.

Production of LEDs continued to increase in Taiwan. Epistar Corp. and Formosa Epitaxy Inc. announced increases in blue LED production. Epistar planned to double monthly capacity of blue LED chips to 120 million units, by installing six new MOCVD machines, and Formosa Epitaxy was increasing its output from 40 million units per month to 60 million (Compound Semiconductor.net, 2004g§). Giga Epitaxy Technology, a manufacturer of GaAs-base epitaxial wafers, was scheduled to begin production of aluminum gallium arsenide (AlGaAs) LED chips in July. The new line, which has an expected capacity of 20,000 square inches per month, will produce chips for red LEDs using liquid phase epitaxy (Compound Semiconductor.net, 2004f§). Epitech Corp. ordered seven MOCVD reactors to increase production of its AlGaInP-base red, orange, and yellow-green ultra-high-brightness LEDs. Epitech also ordered additional reactors for production increase for its GaN-base blue, green, ultraviolet, and white ultra-high-brightness LEDs (Compound Semiconductor, 2004d).

United Kingdom.—Despite the startup of a commercial foundry service at its 6-inch-diameter GaAs wafer facility in Caswell in 2003, Bookham Technology plc decided to cease GaAs production at its Caswell facility in May 2004. Although the 6-inch-diameter line had not lost any major customers, the company decided that the outlook for obtaining additional customers was poor (Stevenson, 2004a).

Current Research and Technology

Spire Corp. was awarded a $99,677 Phase I SBIR contract from the U.S. Army to carry out research towards development of a noninvasive blood-glucose monitor using terahertz radiation generated by a quantum cascade laser. Terahertz radiation has wavelengths that are longer than visible and infrared, but shorter than microwaves, and may be the only radiation source that can separate glucose from other substances. Spire's terahertz quantum cascade laser consists of hundreds of nanometer-thick GaAs-base layers, which would eliminate the need to draw blood samples by finger pricking. The project follows from Spire's $99,000 Phase I small business technology transfer research contract, involving collaboration with the University of Illinois at Urbana-Champaign, to use a new design to produce epitaxial structures cost-effectively. Terahertz radiation sources could have a broad range of applications, including biological agent detection, DNA structure identification, and a number of medical diagnostic techniques (Compound Semiconductor.net, 2004k§, l§).

Researchers at the Tokyo Institute of Technology have fabricated transparent flexible thin-film transistors (TFTs) containing an amorphous indium gallium zinc oxide (InGaZnO) active channel. TFTs are fundamental building blocks for microelectronics such as flat-panel displays. The devices, when combined with transparent circuit technology, could lead to applications such as integrating display functions onto car windshields. Although InGaZnO is not the only material to be investigated for flexible electronic applications, its field-effect mobility is significantly higher than the well-established alternatives, hydrogenated amorphous silicon and pentacene. InGaZnO also is optically transparent from 390 to 3,200 nm, so unlike silicon-base devices, it is suitable for fabrication of transparent circuits (Compound Semiconductor.net, 2004d§).

HRL Laboratories LLC developed a novel indium arsenide-aluminum antimonide-aluminum gallium antimonide detector that allows an order-of-magnitude improvement in the sensitivity of millimeter-wave imaging systems. The millimeter-wave spectrum allows detectors to see through obstructions much more effectively than other imaging bands such as the infrared. Prototype millimeter-wave cameras are already being developed to detect concealed weapons and explosives hidden beneath clothing. Navigation applications include enhanced air, land, and sea guidance through poor visibility conditions such as fog, rain, sandstorms, and smoke. HRL Laboratories has produced and delivered several hundred thousand diodes to Trex Enterprises Corp. in San Diego, CA, for its advanced camera that is under development. HRL Laboratories is a research and development laboratory jointly owned by Boeing, General Motors Corp., and Raytheon Co. (Compound Semiconductor.net, 2004c§).

A team of engineers from Boeing, Entech Inc., and NASA's Glenn Research Center have deployed and tested what is believed to be the first ever terrestrial triple-junction solar array rated at more than 1 kW. The achievement could improve solar power generation in space using high-voltage arrays. It also demonstrated that future terrestrial concentrator arrays based on triple-junction GaInP/GaAs/germanium cells could achieve much better performance at an affordable price. The solar concentrator array, which was deployed near the summit of Mount Haleakala, on the island of Maui in Hawaii, used 240 Spectrolab solar cells to convert sunlight into energy. Two concentrator modules formed the array. According to the team, the peak power output of one of the concentrator modules reached 670 watts, almost twice that of a standard module based on silicon solar cells. The typical energy output of the array was quoted as 16 kilowatthours per day (Compound Semiconductor.net, 2004m§).

Fujitsu Laboratories Ltd. developed a low-cost manufacturing process for GaN HEMTs that uses substrates typically used for LED production, thereby reducing costs to one-third of the conventional cost. Fujitsu says that it can make the HEMTs on a conducting SiC substrate rather than the more conventional—and much more expensive—semi-insulating SiC. The new process used HVPE to deposit a 10-micrometer layer of aluminum nitride on SiC. The GaN HEMT layer was then grown by MOCVD. The company planned to implement the new production technology with commercial devices expected in 1 to 2 years (Compound Semiconductor.net, 2004b§).

Scientists at Sharp Laboratories of Europe (SLE) have produced the world's first blue-violet laser diodes fabricated using MBE. Grown on a sapphire substrate, the indium gallium nitride (InGaN) multiple-quantum-well lasers operate at room temperature with an output wavelength of 400 nm. SLE says that it has a patented MBE system that has been specifically designed for growing GaN devices. The lasers currently operate in pulsed mode, but for commercial applications, a continuous-wave device would be required (Compound Semiconductor, 2004h).

Engineers at Sony have made an optical head that is compatible with Blu-ray, DVD, and CD recording media. Capable of playing and recording Blu-ray discs, as well as conventional DVD and CD media, the optical head prototype features lasers emitting at 405 nm, 660 nm, and 785 nm in a single package. Although Sony's laser chip package is said to be a single unit, it actually contains two separate chips. A chip containing the GaAs-base red and near-infrared sources sits on top of the GaN-base device required for blue-violet emission. According to the company, the three sources will not emit light simultaneously, meaning that the three individual media types could not all operate at the same time. Sony says that it is targeting commercialization of the three-wavelength head within 2 years. It planned to reduce the number of parts used and improve reliability (Compound Semiconductor.net, 2004j§).

A U.S. collaboration has reduced levels of *E. coli* bacteria in water by more than five orders of magnitude using 280 nm excitation from GaN-base ultraviolet LEDs. The experiment was conducted at the University of Maine, with input from local company Hydro-Photon Inc. Hydro-Photon's next project, which also forms part of Defense Advanced Research Projects Agency's Semiconductor Ultraviolet Optical Sources (SUVOS) program, involves developing inline water treatment for the armed forces (Stevenson, 2004b). The goal of the SUVOS program is to use the unique characteristics of wide bandgap semiconductors, such as GaN, to produce optical sources operating in the ultraviolet portion of the spectrum that can be integrated into modules and subsystems for biological agent detection, non-line-of-sight covert communications, water purification, equipment and personnel decontamination, and white light generation.

Outlook

According to Strategy Analytics, GaAs revenue growth from 2004 to 2005 will be about 1% compared with an increase of 7% from 2003 to 2004. The company expected that sales growth would accelerate during 2006 and 2007, before tailing off again towards 2009. The predicted fall in growth in 2005 reflects the fluctuations in the cell phone market, which Strategy Analytics estimated accounts for 52% of sales of GaAs microelectronic components. The company expects handset shipments to increase by only 6% to 7% this year, far less than the 25% to 26% growth experienced between 2003 and 2004. The company also expected that application areas such as wireless local area networks and automotive radar would provide further opportunities for growth in the GaAs industry, but these emerging markets would not grow enough to free the GaAs industry from its cellular handset dependency by 2009. RFMD's manager of the company's Nokia product line predicted that the GaAs content of a cellular telephone would grow by 40% to about 3.4 square millimeters (mm^2) per phone by 2007 and to 4 mm^2 by 2009. This would be accomplished by increasing use of GaAs pHEMTs in antenna switches (Hatcher, 2005).

According to a report by Strategies Unlimited, the value of the worldwide GaN device sector would rise to $7.2 billion in 2009 from $3.2 billion in 2004. Although LED applications dominated the GaN market in 2004, non-LED applications of the technology will account for 17% of the market by 2009. Strategies Unlimited predicts that the blue laser diode market will account for $900 million in 2009, or a 13% share of the overall GaN device industry. Significant shipments of GaN-base blue-violet laser diodes were expected in the second half of 2005 as the DVD industry launches its next-generation recorders and players. For GaN-base electronic devices, the principal application will be HEMTs for use in power amplifiers in base stations for mobile networks and for the emerging fixed wireless base station market. Also according to the report, 394 universities and research centers and 232 commercial firms worldwide were involved in GaN development in 2004 (Compound Semiconductor, 2005).

The total LED market was projected to increase from about $4.7 billion in 2004 to $6.8 billion by 2008, according to market analyst firm iSuppli Corp.—a compound average annual growth rate of 13%. Aside from traditional LED applications in simple displays and indicator lights, LCD backlighting was the biggest single sector for the technology with about 25% of the overall market in 2004. By 2008, decorative lighting and general illumination will gain market share at the expense of traditional LED applications. In terms of materials, the market for GaN-base LEDs was expected to grow faster than that for AlGaInP, but despite this, AlGaInP was expected to maintain its larger market share through 2008. The share of the market driven by cellular telephone keypad backlighting was expected to decline because of pricing pressures and handset manufacturers using fewer devices in their products. Part of the decline can be attributed to the predicted slowdown in the growth of the cellular telephone market itself. This sector was predicted to continue to grow, but at a slower rate than in recent years (Hatcher, 2004b).

According to executives from TriQuint Semiconductor Inc., automotive radar will be the next high-volume application for GaAs monolithic microwave integrated circuits, and they predict that use of GaAs-base collision-avoidance radar operating at 77 gigahertz (GHz) likely will be driven by government regulations on car safety. Future systems will use 77-GHz technology for both long- and short-range radar; 24-GHz radar is currently used in short-range applications (Compound Semiconductor, 2004n).

References Cited

Compound Semiconductor, 2004a, Arima acquires Kingmax AlGaInP capacity: Compound Semiconductor, v. 10, no. 2, March, p. 18.
Compound Semiconductor, 2004b, ATMI sells its GaN business to Cree for $10.25 million in cash: Compound Semiconductor, v. 10, no. 4, May, p. 6.
Compound Semiconductor, 2004c, Emcore wins Boeing solar cell contract: Compound Semiconductor, v. 10, no. 3, April, p. 10.
Compound Semiconductor, 2004d, Epitech ramps GaN and AlGaInP epiwafers: Compound Semiconductor, v. 10, no 10, October, p. 12.
Compound Semiconductor, 2004e, Japanese giants size up blue laser production: Compound Semiconductor, v. 10, no. 9, October, p. 5.
Compound Semiconductor, 2004f, Lumileds opens factory in Malaysia: Compound Semiconductor, v. 10, no. 6, July, p. 5.
Compound Semiconductor, 2004g, Picogiga grows GaN epiwafers on silicon: Compound Semiconductor, v. 10, no. 2, March, p. 13.
Compound Semiconductor, 2004h, Sharp fabricates first blue laser diode using MBE: Compound Semiconductor, v. 10, no. 1, January-February, p. 5.
Compound Semiconductor, 2004i, Showa Denko builds plant to produce blue HB-LEDs: Compound Semiconductor, v. 10, no. 11, December, p. 10.
Compound Semiconductor, 2004j, Sony and Samsung use LED-backlight technology in televisions and monitors: Compound Semiconductor, v. 10, no. 8, September, p. 12.
Compound Semiconductor, 2004k, TDI demonstrates 6 inch GaN epitaxy: Compound Semiconductor, v. 10, no. 11, December, p. 5.

Compound Semiconductor, 2004l, Teledyne set to acquire Celeritek's defense arm: Compound Semiconductor, v. 10, no. 7, August, p. 8.
Compound Semiconductor, 2004m, Toyoda Gosei builds second GaN factory: Compound Semiconductor, v. 10, no. 6, July, p. 9.
Compound Semiconductor, 2004n, TriQuint tips automotive radar: Compound Semiconductor, v. 10, no. 5, June, p. 5.
Compound Semiconductor, 2005, Non-LED applications set to bolster GaN sector: Compound Semiconductor, v. 11, no. 4, May, p. 10.
Hatcher, Michael, 2004a, Cree spells out $300 m expansion plan: Compound Semiconductor, v. 10, no. 8, September, p. 5.
Hatcher, Michael, 2004b, LCD backlighting continues to thrive as pricing pressure bites: Compound Semiconductor, v. 10, no. 11, December, p. 21-24.
Hatcher, Michael, 2004c, Production ramps in Asia as cell phones push up HB-LED demand: Compound Semiconductor, v. 10, no. 3, April, p. 25-29.
Hatcher, Michael, 2004d, Procomp scandal engulfs Suntek: Compound Semiconductor, v. 10, no. 7, August, p. 5.
Hatcher, Michael, 2005, Switches will boost GaAs use in cell phones: Compound Semiconductor, v. 11, no. 4, May, p. 10.
Stevenson, Richard, 2004a, Bookham halts 6 inch GaAs production at Caswell: Compound Semiconductor, v. 10, no. 6, July, p. 8.
Stevenson, Richard, 2004b, UV LEDs reduce water bacteria levels: Compound Semiconductor, v. 10, no. 5, June, p. 13.
Stevenson, Richard, 2004c, WIN–GCT foundry to ramp up capacity: Compound Semiconductor, v. 10, no. 11, December, p. 5.
Whitaker, Tim, 2004, Start-up produces blue LEDs using 'dismissed' technique: Compound Semiconductor, v. 10, no. 7, August, p. 23.

Internet References Cited

Compound Semiconductor.net, 2004a (February 11), II-VI and SET enter epiwafer marketing deal, accessed February 24, 2004, at URL http://www.compoundsemiconductor.net/articles/news/8/2/13/1.
Compound Semiconductor.net, 2004b (December 22), AlN epilayer slashes cost of GaN HEMT, accessed May 13, 2005, at URL http://www.compoundsemiconductor.net/articles/news/8/12/21/1.
Compound Semiconductor.net, 2004c (March 16), HRL develops InAs/GaAlSb mm-wave sensor, accessed March 17, 2004, at URL http://www.compoundsemiconductor.net/articles/news/8/3/16/1.
Compound Semiconductor.net, 2004d (November 30), InGaZnO shows transparent transistor promise, accessed December 2, 2004, at URL http://www.compoundsemiconductor.net/articles/news/8/11/26/1.
Compound Semiconductor.net, 2004e (March 16), Low prices force cuts in gallium production, accessed March 16, 2004, at URL http://www.compoundsemiconductor.net/articles/news/8/3/15/1.
Compound Semiconductor.net, 2004f (May 14), News in brief—LED manufacture and SiC wafers, accessed May 19, 2004, at URL http://www.compoundsemiconductor.net/articles/news/8/5/11/1.
Compound Semiconductor.net, 2004g (April 20), News in brief—LED production, Sony and Unaxis, accessed April 15, 2005, at URL http://www.compoundsemiconductor.net/articles/news/8/4/15/1.
Compound Semiconductor.net, 2004h (February 23), RFMD ramps next-generation PA production, accessed February 25, 2004, at URL http://www.compoundsemiconductor.net/articles/news/8/2/24/1.
Compound Semiconductor.net, 2004i (December 20), RFMD ramps processing with $75 million plan, accessed January 11, 2005, at URL http://www.compoundsemiconductor.net/articles/news/8/12/19/1.
Compound Semiconductor.net, 2004j (May 25), Sony makes triple-wavelength laser source, accessed May 26, 2004, at URL http://www.compoundsemiconductor.net/articles/news/8/5/21/1.
Compound Semiconductor.net, 2004k (August 24), Spire hopes to ease diabetics' lives, accessed August 27, 2004, at URL http://www.compoundsemiconductor.net/articles/news/8/8/19/1.
Compound Semiconductor.net, 2004l (June 28), Spire wins funding for terahertz laser research, accessed March 29, 2005, at URL http://www.compoundsemiconductor.net/articles/news/8/6/30/1.
Compound Semiconductor.net, 2004m (June 14), Triple-junction array generates kilowatt power, accessed May 13, 2005, at URL http://www.compoundsemiconductor.net/articles/news/8/6/16/1.
Geo Specialty Chemicals Inc., 2005 (January 3), GEO Specialty Chemicals announces prompt emergence from Chapter 11, accessed March 22, 2005, at URL http://www.geosc.com/about_news.cfm#Jan3.
Gold Canyon Resources Inc., 2004 (November 10), Gold Canyon activity update on Springpole gold project and Cordero gallium project, accessed March 22, 2005, at URL http://www.goldcanyon.ca/05NewsReleases/nr10nv04.pdf.
LaborLawTalk.com, [undated], Dictionary, accessed April 14, 2005, at URL http://encyclopedia.laborlawtalk.com/HD-DVD.
Metal-Pages, 2004a (October 4), Chalco subsidiary to produce Ga, accessed October 5, 2004, via URL http://www.metal-pages.com.
Metal-Pages, 2004b (November 12), Hengyang Fenghuang focusing on gallium, accessed November 20, 2004, via URL http://www.metal-pages.com.
Metal-Pages, 2004c (June 10), Shandong Aluminium restarts gallium production, accessed June 21, 2004, via URL http://www.metal-pages.com.
Rusmet.net, 2004 (March 12), Major Kazakh metallic gallium producing workshop closed, accessed December 16, 2004, at URL http://www.rusmet.net/news.php?act=by_id&news_id=767.
Sensors Unlimited Inc., 2004 (October 13), Sensors Unlimited introduces the world's smallest dual wavelength, visible & near-infrared camera, accessed October 14, 2004, at URL http://www.sensorsinc.com/downloads/PR_101304.pdf.
Spectrolab Inc., 2004 (January 14), Spectrolab solar cells power latest Mars exploration vehicles, accessed February 5, 2004, at URL http://www.spectrolab.com/com/news/news-detail.asp?id=154.
U.S. Department of Commerce, 2004 (September), ATP project brief—Low cost, high efficiency chip scale LED lamp, accessed May 13, 2005, at URL http://www.nist.gov/public_affairs/factsheet/atp2004/00-00-7011_factsheet.htm.
U.S. Department of Energy, 2005 (January), 2005 project portfolio—Solid state lighting, accessed May 15, 2005, at URL http://www.netl.doe.gov/ssl/PDFs/SSL%20Portfolio%202005_2-03.pdf.

GENERAL SOURCES OF INFORMATION

U.S. Geological Survey Publications

Gallium. Ch. in Mineral Commodity Summaries, annual.
Gallium, Germanium, and Indium. Ch. in United States Mineral Resources, Professional Paper 820, 1973.
Historical Statistics for Mineral Commodities in the United States. Open File Report OF-01-006, 2001.

Other

Compound Semiconductor.
Economics of Gallium, The (7th ed.). Roskill Information Services Ltd., 2002.

Gallium. Ch. in Mineral Facts and Problems, U.S. Bureau of Mines Bulletin 675, 1985.
Gallium and Gallium Arsenide—Supply, Technology, and Uses. U.S. Bureau of Mines Information Circular 9208, 1988.
LEDs Magazine.
Mining Journal.
Minor Metals in the CIS. Roskill Information Services Ltd., 1997.

TABLE 1
SALIENT U.S. GALLIUM STATISTICS[1]

(Kilograms unless otherwise specified)

	2000	2001	2002	2003	2004
Production	--	--	--	--	--
Imports for consumption	39,400	27,100	13,100	14,300	19,400
Consumption	39,900	27,700	18,600	20,100	21,500
Price dollars per kilogram	640 [2]	640 [2]	530 [3]	411 [3]	494 [3]

-- Zero.

[1]Data are rounded to no more than three significant digits.

[2]Source: American Metal Market.

[3]Estimate based on average value of U.S. imports of high-purity gallium.

TABLE 2

U.S. CONSUMPTION OF GALLIUM, BY END USE[1, 2]

(Kilograms)

End use	2003	2004
Optoelectronic devices:		
Laser diodes and light-emitting diodes	7,630	6,930
Photodetectors and solar cells	524	809
Integrated circuits:		
Analog	8,090	9,890
Digital	51	63
Research and development	3,720	3,690
Other	94	111
Total	20,100	21,500

[1]Data are rounded to no more than three significant digits; may not add to totals shown.

[2]Includes gallium metal and gallium compounds.

TABLE 3

STOCKS, RECEIPTS, AND CONSUMPTION OF GALLIUM, BY GRADE[1, 2]

(Kilograms)

Purity	Beginning stocks	Receipts	Consumption	Ending stocks
2003:				
99.99% to 99.999%	355	17	32	340
99.999%	224	5,600	5,090	729
99.99999% to 99.999999%	245	530	649	126
Total	824	6,140	5,770	1,200
2004:				
99.99% to 99.999%	340	151	35	456
99.999%	729	5,720	5,330	1,120
99.99999% to 99.999999%	126	508	507	127
Total	1,200	6,380	5,870	1,710

[1]Consumers only.

[2]Data are rounded to no more than three significant digits; may not add to totals shown.

TABLE 4
ESTIMATED YEAREND GALLIUM PRICES

(Dollars per kilogram)

Gallium metal	2003	2004
99.9999%-pure, average value of U.S. imports	411	494
99.99%-pure, average value of U.S. imports	225	192

TABLE 5
U.S. IMPORTS FOR CONSUMPTION OF GALLIUM (UNWROUGHT, WASTE, AND SCRAP), BY COUNTRY[1]

Country	2003 Quantity (kilograms)	2003 Value[2]	2004 Quantity (kilograms)	2004 Value[2]
China	5,540	$1,220,000	4,740	$1,050,000
France	936	440,000	1,170	569,000
Germany	--	--	37	15,800
Hungary	1,300	371,000	2,300	476,000
Japan	634	181,000	5,380	828,000
Russia	1,800	362,000	1,740	508,000
Ukraine	2,720	597,000	3,000	420,000
United Kingdom	348	109,000	182	46,700
Other	974	240,000	864	214,000
Total	14,300	3,520,000	19,400	4,130,000

-- Zero.

[1]Data are rounded to no more than three significant digits; may not add to totals shown.

[2]Customs value.

Source: U.S. Census Bureau.

TABLE 6

U.S. IMPORTS FOR CONSUMPTION OF GALLIUM ARSENIDE WAFERS, BY COUNTRY[1]

	Undoped				Doped			
	2003		2004		2003		2004	
Country	Quantity (kilograms)	Value[2]	Quantity (kilograms)	Value[2]	Quantity (kilograms)	Value[2]	Quantity (kilograms)	Value[2]
Canada	4	$16,000	2,260	$28,500	30	$88,300	25	$102,000
China	15	9,450	27	9,380	24,800	23,500,000	12,000	19,700,000
Finland	--	--	--	--	11,200	12,700,000	8,750	10,400,000
Germany	--	--	103	4,960	22,200	22,700,000	31,500	27,600,000
Japan	13,000 r	341,000	111	92,900	36,700	30,900,000	80,500	50,800,000
Korea, Republic of	--	--	14	10,200	14,500	6,930,000	64,500	23,800,000
Russia	78	135,000	502	182,000	44	101,000	88	215,000
Singapore	13	84,700	557	116,000	166	789,000	257	692,000
Taiwan	36	167,000	3	14,900	8,980	8,390,000	22,200	12,500,000
United Kingdom	1,320	26,500	2	17,700	1,600	304,000	164	451,000
Other	12 r	7,540 r	6	4,590	7,170 r	1,100,000 r	6,440	7,300,000
Total	14,400 r	788,000 r	3,580	481,000	127,000	107,000,000 r	226,000	153,000,000

r Revised. -- Zero.

[1]Data are rounded to no more than three significant digits; may not add to totals shown.

[2]Customs value.

Source: U.S. Census Bureau.

TABLE 7
ESTIMATED WORLD ANNUAL PRIMARY GALLIUM PRODUCTION CAPACITY, DECEMBER 31, 2004[1]

(Metric tons)

Country	Capacity
Australia[2]	50
China	47
Germany	35
Hungary	8
Japan	20
Kazakhstan	20
Russia	19
Slovakia	8
Ukraine	3
Total	210

[1]Includes capacity at operating plants as well as at plants on standby basis.

[2]Standby capacity as of December 31, 2004.